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Carbon budget and seasonal carbon dioxide emission from a central Ohio Luvisol as influenced by wheat residue amendment

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Abstract

Enhancement of soil organic carbon (SOC) stocks through mulching has been proposed, and although this practice can alter several soil properties, its impact on the temporal variability of carbon dioxide (CO_2) emission from soils has not been widely investigated. To that end, we monitored CO_2 fluxes from a central Ohio Luvisol (fine, mixed, mesic Aeric Ochraqualf) amended with wheat (*Triticum aestivum* L.) straw applied at rates of 0 (M0), 8 (M8) and 16 (M16) Mg dry matter ha^{-1} per year and supplemented with fertilizer (244 kg N ha^{-1} per year) or without. The experimental design was a randomized complete block design with three replications. The intensity of CO_2 emission was higher in the late winter (mean: 2.79 g CO_2-C m^{-2} per day) and summer seasons (2.45 g CO_2-C m^{-2} per day) and lowest in the autumn (1.34 g CO_2-C m^{-2} per day). While no significant effect of N fertilization on CO_2 emission was detected, soil mulching had a significant effect on the seasonal variation of CO_2 fluxes. The percentage of annual CO_2 emitted during the winter and spring was similar across treatments (17–22%); however, 43% of the annual CO_2 loss in the M0 plots occurred during the summer as opposed to 26% in the mulch treatments. A close relationship ($F = 0.47X + 4.45$, $R^2 = 0.97$, $P < 0.001$) was found between annual CO_2 flux (F, Mg CO_2-C ha^{-1}) and residue-C input (X, Mg C ha^{-1}). Litter and undecomposed residue amounted to 0.32 and 0.67 Mg C ha^{-1} per year in the M8 and M16 plots, respectively. After 4 years of straw application, SOC stocks (0–10 cm) were 19.6, 25.6 and 26.5 Mg C ha^{-1} in the M0, M8 and M16 treatments, respectively. The results show that soil mulching has beneficial effect on SOC sequestration and strongly influence the temporal pattern of CO_2 emission from soils.

Keywords: Soil mulching; Carbon dioxide; Carbon sequestration; Seasonal CO_2 flux; C budget; Luvisol, central Ohio

1. Introduction

Increased concentration of carbon dioxide (CO_2) in the atmosphere (0.4–0.5% per year) has been linked to the projected warming of world climate (Watson et al., 1992). World soils represent a major component of the global carbon cycle, given that (i) soils are the second largest terrestrial C reservoir estimated at 1500 Pg C to 1 m depth (Eswaran et al., 1993), (ii) the soil–plant system and the pedosphere–atmosphere interface are sites of intense C exchange with 10% of atmospheric C passing through soils annually (Raich and Tufekcioglu, 2000), and (iii) the capacity of soils for long-term storage of photosynthetically fixed C. This capacity provides a mechanism for reducing the rate of atmospheric CO_2 buildup and increasing soil organic carbon (SOC) reserves.

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Proposed C sequestration strategies generally involve management practices which increase crop residue input while minimizing C losses (Lal et al., 1998; Follett, 2001). These two basic criteria can be met with soil mulching, an agricultural practice commonly used in conjunction with conservation tillage in which crop residue is applied to the soil surface in order to protect against erosion, minimize evaporative water loss (Sauer et al., 1996) and promote nutrient cycling (Tian et al., 1993). In addition, by altering soil albedo and thermal properties (Franzluebbers et al., 1995; Sauer et al., 1996), surface-applied mulch could affect SOC mineralization and CO_2 production given the strong control of soil temperature on these processes (Raich and Schlesinger, 1992; Franzluebbers et al., 1995; Fortin et al., 1996; Mielnick and Dugas, 2000).

The decomposition of residue in soils involves the mineralization of the labile C fractions by decomposer organisms resulting in the formation of microbial by-products and accumulation of recalcitrant organic compounds which incorporate the stable SOC pools. Environmental variables (e.g. water and temperature; Schomberg et al., 1994), residue quality (Tian et al., 1993; Trinsoutrot et al., 2000), and placement (Trinsoutrot et al., 2000) affect residue decomposition in soils. Both the conversion of residue-C into stable SOC (humification) and the mineralization of SOC are accompanied with CO_2 production, and thereby contribute to the return of some of the added C to the atmosphere. Soil C storage, therefore, is determined by the balance between residue-C addition and respiratory C losses. A complete assessment of soil mulching and C sequestration therefore requires estimates of CO_2 exchange between mulch-covered soils and the atmosphere.

Studies have been made of CO_2 emission from soils in relation to tillage (Franzluebbers et al., 1995; Fortin et al., 1996; Wagai et al., 1998), crop rotation (Rochette et al., 1992; Franzluebbers et al., 1995), climate (Fortin et al., 1996; Mielnick and Dugas, 2000) and ecosystems management (Wagai et al., 1998; Mielnick and Dugas, 2000). Although data regarding CO_2 evolution during straw decomposition in the laboratory have been published (Corbeels et al., 2000; Trinsoutrot et al., 2000), there is limited information regarding emission of CO_2 from mulch-covered fields. A long-term research project was initiated in 1996 to study the effect of surface-applied wheat (*Triticum aestivum* L.) residue on C sequestration in a central Ohio Luvisol. As a previous study on a similar soil had suggested a N limitation on wheat straw decomposition (Duiker and Lal, 1999), mineral N was added to some of the plots to alleviate this limitation. It is hypothesized that supplementing residue with N fertilizer alters biological activity and, consequently, CO_2 flux in mulch-covered soils.

Thus, the objectives of this paper were to: (i) determine the effect of mulch application rate and N fertilization on CO_2 emission from uncropped soils amended with various amounts of wheat residue, and (ii) construct an annual C budget for the different residue treatments.

2. Materials and methods

2.1. Experimental description

This study was conducted at the Waterman farm of the Ohio State University located in Columbus (longitude 83°01′W and latitude 40°00′N), where a study investigating the effect of wheat (*T. aestivum* L.) residue fertilization on C sequestration was initiated in 1996. The soil is a Crosby silt loam (Soil Taxonomy: fine, mixed, mesic Aeric Ochraqualf; FAO classification: Stagnic Luvisol) developed from glacial till. Long-term mean annual temperature and precipitation are 11 °C and 967 mm, respectively. Precipitation and air temperature were recorded at a nearby (∼200 m) weather station and compiled by the Ohio Agricultural Research and Development Center (OARDC, Wooster, OH). During the year 2000, total rainfall and average air temperature were 1126 mm and 11.4 °C, respectively (Fig. 1).

The experimental design included three (3) mulch application rates (bare: 0, low: 8 and high: 16 Mg dry matter ha^{-1} per year) and two (2) levels of fertilizer application: no fertilizer (−F), and fertilizer applied (+F). Fertilizer was broadcast-applied at an annual rate of 244 kg N ha^{-1} (184 kg N ha^{-1} as urea and 60 kg ha^{-1} of N–P–K). The resulting six mulch × nutrient treatments were triplicated and randomly assigned to 18 experimental plots (5 m × 5 m) in a randomized complete block design. Each year, baled wheat straw was applied in the spring followed

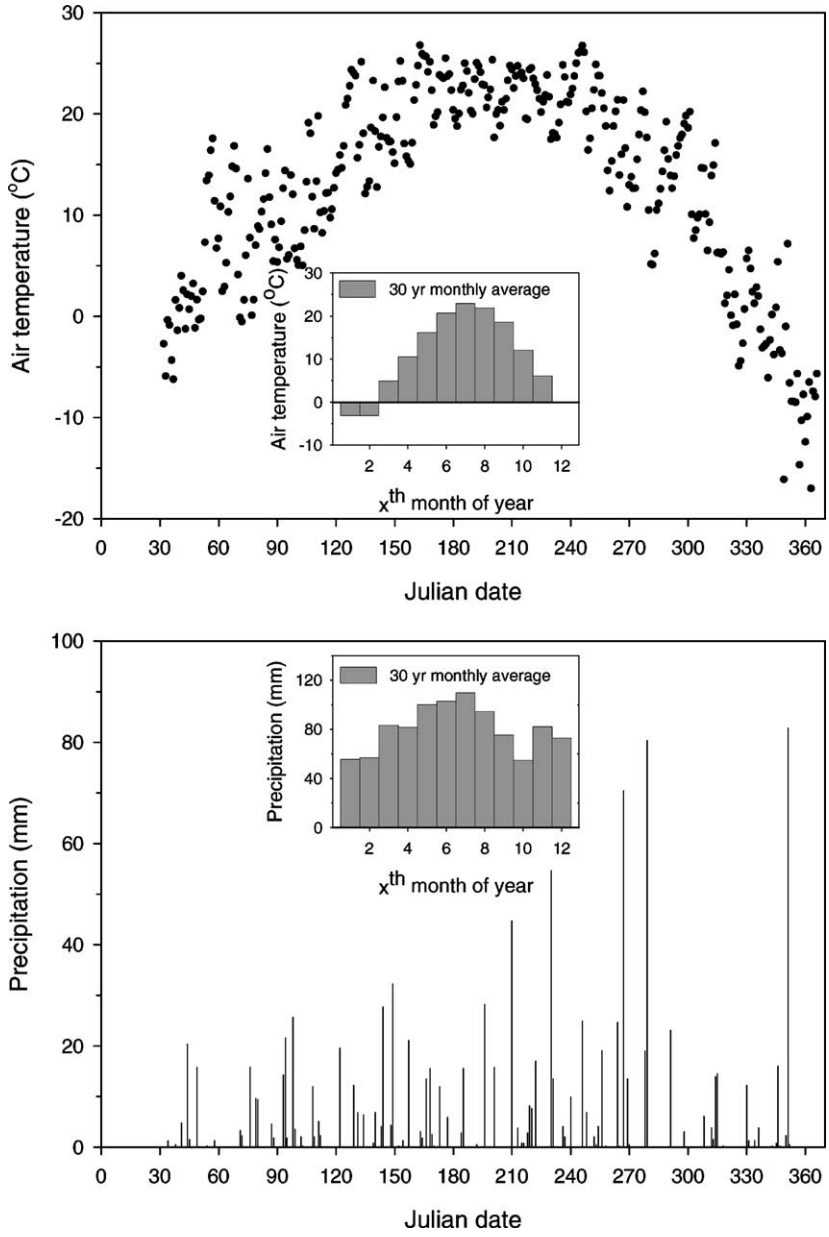

Fig. 1. Daily temperature and precipitation at the study site (Columbus, OH) in the year 2000. Long-term monthly weather data are presented in the graph insets.

by fertilizer application in the late spring to early summer. There was no crop grown on the plots and no operation was performed to mechanically incorporate the residue into the soil. As noted in Duiker and Lal (1999), compaction of the residue occurred rapidly after its application due to the abundant precipitation typically recorded during the spring (Fig. 1). During the period 1996–2000, 39–56% of the annual precipitation (mean: 1009 mm) occurred between March and June. As needed (once or twice a year), glyphosate

(phosphonomethyl glycine) was applied for weed control.

2.2. Monitoring of CO_2 flux

Daily CO_2 flux was monitored between February and November 2000 by the closed soil chamber method. Details regarding construction and operation of the chamber used are provided elsewhere (Jacinthe and Dick, 1997) and are briefly outlined here. The chamber, made of PVC material, consisted of two parts: a bottom section (30 cm long × 15 cm diameter) inserted 10 cm into the ground, and a lid fitted with a gas sampling port. When samples were taken, the chamber was closed with the lid and CO_2 accumulation was monitored over 90 min. Air samples (∼10 ml) were withdrawn from the chamber headspace and stored in evacuated vials (5 ml) fitted with gray butyl rubber septa (Wheaton, Millville, NJ).

Once installed, the gas sampling chambers (two per plots) remained in place during the entire monitoring period (February–November 2000). The first sampling occurred 1 week after installation of the chambers and proceeded at a frequency of approximately twice a month. Gas sampling was typically conducted between 11:00 and 13:00 h when daily fluxes are expected to be maximum (Rochette et al., 1992; Bajracharya et al., 2000).

Daily flux of CO_2 (F, g CO_2-C m^{-2} per day) was computed as

$$F = \left(\frac{\Delta C}{\Delta t}\right)\left(\frac{V}{A}\right)k \quad (1)$$

where $\Delta C/\Delta t$ is the rate of CO_2 accumulation inside the chamber (g CO_2-C m^{-3} air min^{-1}), V the chamber volume (m^3), A the area circumscribed by the chamber (m^2), and k the time conversion factor (1440 min per day).

2.3. Soil sampling and residual straw accounting

Soil samples (0–10 cm depth), including 5 cm diameter soil cores, were collected in May 2000 for determination of organic C and bulk density. Before the sixth application of wheat straw to the plots, residue remaining on the surface was collected and weighted. These measurements in conjunction with the CO_2 flux data were used in a mass balance C budget for the different residue treatments.

2.4. Analytical

Air samples were analyzed for CO_2 with a Shimadzu GC-14A gas chromatograph equipped with a thermal conductivity detector and a 90 cm × 0.3 cm Hayesep D column (Alltech, Deerfield, IL). Helium was used as carrier gas at a flow rate of 20 ml min^{-1}. Column and detector temperatures were 50 and 150 °C, respectively. Standard CO_2 used for instrument calibration were obtained from Alltech (Deerfiled, IL).

Analysis of soil sample for C content was conducted by the dry combustion method (900 °C) on a Carlo-Erba C–N analyzer. Air-dried soil that had passed though a 250 μm sieve was used in the analysis.

2.5. Data analysis

A distribution analysis of the CO_2 flux data was first performed for each sampling date and for the entire monitoring period. That analysis showed that, for most sampling dates, a square root or a log transformation of the data was needed in order to satisfy the normal distribution assumption of the analysis of variance (ANOVA). The transformed data were subsequently submitted to a repeated measured ANOVA (Littell, 1989) with mulch rate and fertilization as the treatment factors and sampling date as the repeated measure factor.

Data distribution and ANOVA analysis were carried out by the procedures Univariate Normal and GLM Repeated available in SAS (SAS, 1988). The Greenhouse-Geisser adjusted F-values were used to test the significance of sampling date and its interactions. Comparisons between treatment means were carried at the 0.05 level of probability.

3. Results

3.1. Daily CO_2 fluxes

Repeated-measured ANOVA showed an overall significant effect ($P < 0.02$) of mulch application but no significant effect ($P < 0.40$) of N fertilization or its interaction on CO_2 flux. Given this general lack of N fertilization effect, no further discussion of this factor will be made in the paper. The CO_2 flux data were

Table 1
Daily carbon dioxide ($g\,CO_2$-$C\,m^{-2}$ per day) emission from a central Ohio Luvisol as affected by mulch application rate in 2000

Calendar date	Julian date	Mulch application rate ($Mg\,ha^{-1}$ per year)			
		0	8	16	LSD[a]
16 February	47	3.62 ± 3.29[b]	2.00 ± 1.15	1.01 ± 0.63	1.84
25 February	56	1.33 ± 0.49	6.92 ± 9.00	7.86 ± 9.21	8.46
29 February	60	1.49 ± 1.10	2.28 ± 1.24	3.33 ± 1.23	1.29
24 March	84	1.50 ± 1.04	2.22 ± 1.35	6.02 ± 5.09	3.60
31 March	91	0.43 ± 0.26	0.71 ± 0.74	1.20 ± 0.74	0.72
14 April	105	0.98 ± 0.52	2.13 ± 1.84	5.13 ± 3.19	2.62
26 April	117	1.65 ± 1.41	2.81 ± 2.78	1.88 ± 1.96	2.34
4 May	125	0.89 ± 0.50	3.38 ± 3.48	4.33 ± 2.70	2.86
18 May	139	1.25 ± 1.11	1.18 ± 0.96	2.18 ± 2.14	1.68
25 May	146	2.11 ± 1.54	2.02 ± 1.54	1.23 ± 0.83	1.30
9 June	161	1.53 ± 0.48	1.82 ± 2.24	2.19 ± 1.07	1.65
20 June	172	1.65 ± 0.83	1.72 ± 1.39	2.39 ± 1.37	1.28
7 July	189	6.77 ± 3.43	5.75 ± 4.15	5.40 ± 4.59	4.25
21 July	203	0.71 ± 0.29	1.16 ± 0.82	1.17 ± 0.76	0.71
4 August	217	1.42 ± 0.84	2.08 ± 1.13	2.22 ± 1.69	1.46
21 August	234	2.62 ± 2.23	2.08 ± 1.18	2.62 ± 1.81	1.12
7 September	251	1.73 ± 0.79	1.34 ± 1.07	1.40 ± 0.81	0.97
20 September	264	1.03 ± 0.41	2.47 ± 3.02	3.53 ± 2.11	1.83
10 November	315	0.26 ± 0.14	0.29 ± 0.17	0.50 ± 0.28	0.22
All dates		1.73 ± 2.00	2.33 ± 2.22	2.92 ± 3.61	0.68

[a] Least significant difference ($P < 0.05$) comparing fluxes among mulch treatments at a given sampling date.
[b] Daily flux is the mean ± standard deviation of 12 determinations.

thus pooled on the basis of mulch application rates without regard to N fertilization (Table 1).

Measured CO_2 fluxes during the monitoring period ranged from 0.02 to 29.51 $g\,CO_2$-$C\,m^{-2}$ per day, but 92% of the measured fluxes were less than 5 $g\,CO_2$-$C\,m^{-2}$ per day. Frequency analysis showed that the data were positively skewed, with an overall mean and median of 2.45 and 1.49 $g\,CO_2$-$C\,m^{-2}$ per day, respectively. Given the inter-quartile range (2.31 $g\,CO_2$-$C\,m^{-2}$ per day), daily fluxes greater than 4.97 $g\,CO_2$-$C\,m^{-2}$ per day (median + 1.5 inter-quartile) can be defined as outliers (Ott, 1988). Nearly 10% of the recorded fluxes fitted that definition, and a positive relationship ($R^2 = 0.70$, $P < 0.001$) was found between the number of outliers observed during a sampling date and the mean daily CO_2 emission on that day. Although in an experimental plot the two sampling chambers were only 2 m apart, daily fluxes within plots varied by as much as 99.7% (average CV of 40%).

The highest CO_2 fluxes were recorded between JD 47–56 and on JD 189 (Table 1). While daily CO_2 fluxes were generally higher in the residue-treated than in the bare plots, statistical differences were found in only a few sampling occasions. In fact, in some sampling occasions (e.g. JD 47, 146, 189 and 234), the bare plots emitted CO_2 at rates (2.11–6.77 $g\,CO_2$-$C\,m^{-2}$ per day) comparable or even higher than did the mulch treatments (1.01–5.75 $g\,CO_2$-$C\,m^{-2}$ per day). Soil surface conditions (bare, mulch) had a pronounced effect on CO_2 flux during the late winter and fall sampling dates. Both the large CO_2 spikes observed in the late winter and the drop in CO_2 emission during the autumn occurred earlier in the bare plots compared to the mulch treatments.

3.2. Seasonal CO_2 fluxes

Given the CO_2 daily flux patterns (Table 1) and the results of the repeated measured ANOVA, the data were divided into the following four periods corresponding approximately to the seasons of the year: late winter (JD 47–84), spring (JD 91–161), summer

Table 2
Seasonal rate of carbon dioxide emission ($g\,CO_2\text{-}C\,m^{-2}$ per day) from a central Ohio Luvisol as affected by mulch application rate and temperature

Season	Mulch application rate ($Mg\,ha^{-1}$ per year)			Average air temperature[a] (°C)	Total precipitation (mm)
	0	8	16		
Late winter	1.67 b[b]	2.82 ab	3.88 a	7.5	65.53
Spring	1.40 b	2.22 ab	2.82 a	16.4	165.1
Summer	2.48 a	2.35 a	2.53 a	22.3	277.9
Autumn	0.64 b	1.38 ab	2.01 a	14.8	234.8

[a] Average air temperature and cumulative precipitation during the period.
[b] Within a row values followed by the same letter are not significantly different at $P < 0.05$.

(JD 172–251) and autumn (JD 264–315). There were two to seven sampling occasions within each of these periods. Seasonal average CO_2 flux for each experimental plot was computed and summarized in Table 2. Mulch application rate had a significant ($P < 0.025$) effect on the seasonal CO_2 emission with average daily fluxes generally higher in the mulch than in the bare plots. The highest seasonal flux averages were obtained in the late winter (mean: $2.79\,g\,CO_2\text{-}C\,m^{-2}$ per day) and the summer ($2.45\,g\,CO_2\text{-}C\,m^{-2}$ per day), and the lowest ($1.34\,g\,CO_2\text{-}C\,m^{-2}$ per day) in the autumn (Tables 1 and 2). During the summer period, average emission rates were statistically similar across treatments. The bare plots exhibited the greatest variation in seasonal CO_2 fluxes.

Across treatments, total precipitation during a period and average seasonal CO_2 flux (Table 2) were poorly related ($R^2 < 0.22$, $P < 0.83$). However, if the late winter fluxes are excluded, strong correlations (R^2: 0.54–0.98, $P < 0.05$) were found between seasonal CO_2 flux and air temperature; the relationships between these variables remain nonetheless weak (R^2: 0.13, $P < 0.77$) for the high mulch treatment.

The trapezoidal rule was used to compute cumulative seasonal and annual CO_2 emission from each plot. Seasonal CO_2 loss, as a percentage of the annual CO_2 emission was also computed for each treatment (Fig. 2). Across treatments, between 17 and 22% of the annual CO_2 loss occurred during the late winter period. During the summer, this proportion was 43, 27

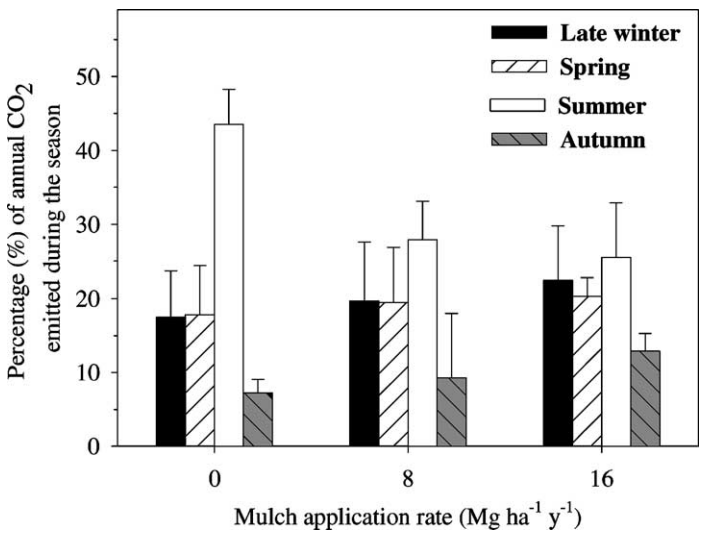

Fig. 2. Cumulative seasonal CO_2 loss as a percentage of the total annual CO_2 emission from a central Ohio Luvisol amended with various amounts of wheat straw. Errors bars indicate ±standard deviation.

Table 3
Mass balance C budget and carbon dioxide emission from a central Ohio Luvisol amended with wheat residue

	Mulch application rate (Mg ha^{-1} per year)		
	0	8	16
Residue-C addition (A)[a]	–	3.52	7.04
Annual CO_2 emission, Mg C ha^{-1}	4.37 ± 0.73 b[b]	6.51 ± 1.19 a	7.73 ± 1.30 a
CO_2 from mulch decomposition (B)	–	2.14[c]	3.36
Undecomposed residue-C (R)	–	0.32 ± 0.06	0.68 ± 0.07
C accrual (S) and unaccounted C (U) [$A - (B + R) = S + U$]	–	1.10	2.99
Measured SOC stock (0–10 cm), Mg C ha^{-1}	19.64 ± 0.91	25.58 ± 0.56	26.49 ± 1.83
Annual rate of C accrual (S)		1.48 ± 0.36	1.71 ± 0.23
Unaccounted C (U)		0	1.28

[a] Unless indicated otherwise, units are Mg C ha^{-1} per year.
[b] Values are means ± standard deviations. Within a row values followed by the same letter are not significantly different at $P < 0.05$.
[c] Computed as CO_2 flux difference between the treatment and bare plots.

and 25% in the bare, low and high mulch treatments, respectively.

3.3. Carbon budget

After 4 years of wheat straw application, SOC stocks (0–10 cm) were 19.6, 25.6 and 26.5 Mg C ha^{-1} in the bare, low and high mulch treatments, respectively (Table 3). Annual CO_2 emission averaged 4.37 ± 0.73 Mg C ha^{-1} in the bare plots and was significantly lower than in the mulch treatments. No statistical difference in annual emission (6.51 ± 1.19 and 7.73 ± 1.30 Mg C ha^{-1}, respectively) was found between the low and high mulch treatments (Table 3). Litter and undecomposed residue found on the surface of plots before the sixth application of wheat straw averaged 3.7 ± 0.7 and 7.8 ± 0.7 Mg ha^{-1}, in the low and high mulch treatments, respectively. These figures corresponded to 6.2–11.2% (average 9.5%) of the mulch applied during the previous 5 years.

A carbon mass balance was constructed for the mulch treatments based on the following four assumptions: (1) the cumulative CO_2 loss during the monitoring period is a measure of annual respiratory C loss, (2) the CO_2 emitted from the bare plot results from mineralization of stable SOC pools, (3) the emission of CO_2 from the mulch treatments is the combined product of wheat residue decomposition (humification) and biological oxidation of stable SOC, and (4) the difference between C addition (A) and the sum of CO_2 emission from residue decomposition (B) and undecomposed residue-C (R) is equivalent to the sum of stable SOC increment (S) and unaccounted residue-C (U) [$A - (B + R) = S + U$]. It follows from the first three assumptions that CO_2 emission attributable to mulch decomposition (B) can be obtained by subtracting bare plot CO_2 flux from mulch treatment emissions. The results (Table 3) of this C budgeting approach showed that the C added to the low mulch plots was accounted for in the stable SOC pool (30%), the undecomposed residue (10%) and as CO_2 emission (60%). However, about 20% of the C added could not be accounted for in the high mulch treatment.

4. Discussion

4.1. Fertilization and CO_2 flux

A positive effect of N fertilization on CO_2 emission was anticipated on the premise that decomposition of N-limited residue could be stimulated (Duiker and Lal, 1999). The lack of a fertilization effect suggests that decomposition was not N-limited and that the soil was capable of gradually releasing mineral N to sustain the activity of the decomposers. Limited or no response of N fertilization on the decomposition of crop residue (Corbeels et al., 2000), forest litter (Castro et al., 1994) and SOC in agricultural soils (Green et al., 1995) has been reported. The lack of a N fertilization effect is not entirely surprising given the reduction in soil microbial biomass C with N fertilization observed at this site (Jacinthe et al., unpublished results), and the reduction in fungal dominance (Lovell et al., 1995)

and the loss of ligninolytic enzyme activity (Carreiro et al., 2000) observed with continuous N addition to ecosystems.

4.2. Effect of wheat straw cover on seasonal CO_2 flux

The seasonal variation in CO_2 fluxes is noteworthy and reflects climatic controls on CO_2 production and emission, and the modulating effect of soil cover on these processes. In snow-covered frozen soils, gas exchange between the soil and the atmosphere is constrained, but soil respiration at depth is not halted. This results in the accumulation of CO_2 in the soil profile during the winter months and its rapid release into the atmosphere during soil thawing events. Field data reported by Burton and Beauchamp (1994) support this scenario. A burst in respiratory activity at spring thaw has also been ascribed to increased availability of soluble organic C released from disrupted soil aggregates (Edwards and Cresser, 1992), and frost-killed soil microorganisms (Skogland et al., 1988). The flush of CO_2 observed during the late winter is likely to be the combined effect of these processes. Its early occurrence (JD 47) in the bare soil suggests that, as air temperature began to rise, these plots warmed up faster than did the residue-amended plots in which delayed (JD 56–84) but more vigorous bursts of CO_2 emission were observed. The largest (15.5–29.5 g CO_2-C m^{-2} per day) CO_2 fluxes recorded during the monitoring period occurred in the mulch treatments during the late winter season (Table 1), and are slightly greater (8.7–11.1 g CO_2-C m^{-2} per day) than those reported by Burton and Beauchamp (1994) for a cultivated Luvisol in Canada during spring thaw.

In response to soil warming during the summer months, a second burst of respiratory activity was observed, but the increase was more pronounced in the bare soils. With average daily fluxes as high as 6.77 g CO_2-C m^{-2} per day (Table 2), 43% of the annual CO_2 loss in this treatment occurred during the summer (Fig. 2). Continued loss of C as CO_2 (4.4 Mg CO_2-C ha^{-1} per year) from the bare plots would probably result in a degradation of soil quality in the long term, as already apparent by the observations of labile C (mineralizable C and microbial biomass C) depletion in this treatment (Jacinthe et al., unpublished results).

Consistent with several previous studies (see reviews by Raich and Schlesinger, 1992; Raich and Tufekcioglu, 2000), a close relationship ($F = 0.47X + 4.45$, $R^2 = 0.97$, $P < 0.001$) was found between annual CO_2 flux (F, Mg CO_2-C ha^{-1}) and residue-C input (X). While in the present study, annual CO_2 fluxes were 4.4, 6.5 and 7.7 Mg CO_2-C ha^{-1} in the 0, 8 and 16 Mg ha^{-1} per year mulch treatments, respectively, Duiker and Lal (2000) reported annual emission rates of 3.8, 5.3, and 6.6 Mg CO_2-C ha^{-1} (15–22% lower) from another central Ohio Luvisol amended with similar amounts of wheat straw. In the latter study, CO_2 fluxes were monitored only between mid-April and October 1997, and that may have resulted in an underestimation of the annual CO_2 emission given that the late winter fluxes (which account for 17–22% of the annual loss) had probably been missed.

4.3. Assessing the C budgeting approach

The mass balance approach described in this paper performed well in the case of the low mulch treatment. In this treatment, the results obtained showed the residue added to the plots was mineralized to CO_2 (60%), contributed to SOC stock increment (30%) and undecomposed (10%). When applied to the high mulch treatment data, the C budgeting technique could only account for 76% of the C added (CO_2 emission: 44, undecomposed: 10, and SOC: 22%). Several factors could contribute to the poor performance of the mass balance approach including earthworm feeding and burrowing activities, the depth of soil sampled for estimating SOC stocks, and modification of soil thermal properties with mulching.

Faunal activity, favored by moisture and temperature conditions in the mulch treatments, may have lead to the transport of residue to depths greater than the 10 cm soil layer sampled for SOC stocks determination. Taking the average rates of alfalfa residue transport by earthworm (2.5 g residue m^{-2} per day) reported by Gallagher and Wollenhaupt (1997), and assuming that worms are actively feeding during only 3 months, they could still contribute to the redistribution of more than 10% (2 Mg residue ha^{-1}) of the residue applied to the high mulch treatment plots. Other reports of residue burial (Knollenberg et al., 1985), soil mixing (Cook and Linden, 1996) and change in the depth-distribution of SOC (Shuster et al., 2001) caused

by deep-burrowing earthworms further support this interpretation. A second factor contributing to the poor performance of the mass balance approach is the difficulty to fully account for undecomposed residue. Undecomposed residue-C was probably underestimated as it was not practical to adequately sample and weigh the small pieces of undecomposed residue in these plots. The use of litter bags in the future is suggested to better quantify the mass of undecomposed residue and thus improve C budget.

Another explanation for the poor performance of the C budgeting approach in the high mulch treatment may be that because the application of residue modifies the soil thermal regime, the bare plots may not be true controls for the mulch plots as far as oxidation of stable SOC is concerned. Higher soil temperature in the bare plots may have resulted in greater mineralization of stable SOC in these plots relative to the mulch treatments. Therefore, mulch-induced CO_2 fluxes in the mulch plots may have been over-corrected resulting in an over-estimation of unaccounted-C in the high mulch treatment. To properly compute mulch-induced CO_2 fluxes, emission from the control (bare) plots must be adjusted to account for temperature and stable SOC mineralization differences. For the 8 Mg ha^{-1} per year mulch treatment, such an adjustment was not necessary because difference in seasonal CO_2 fluxes (Table 2) between the bare plots and this treatment was generally of lesser magnitude than difference with the high mulch treatment. To make the temperature-adjustment for the high mulch treatment (as soil temperature was not measured in the present study), the data from Duiker and Lal (2000) were used to draw the following relationships between air (T_A, °C) and soil temperature (T_S, °C): $T_S = -0.09T_A^2 + 3.43T_A - 3.63$ ($R^2 = 0.98$, $P < 0.01$) for the bare plots, and $T_S = -0.17T_A^2 + 5.97T_A - 31.14$ ($R^2 = 0.83$, $P < 0.06$) for the high mulch treatment. These relationships show that, for an average air temperature of 11.4 °C, T_S in the bare plot was 1.6 times higher than in the high mulch treatments. Then, from the air temperature (Fig. 1) and daily CO_2 flux data (Table 1), and given the relationship f (g CO_2-C m^{-2} per day) $= -0.22 + 0.02T_S^{1.49}$ (Duiker and Lal, 2000), the temperature-adjusted CO_2 flux due to mineralization of stable SOC in the high mulch plots was estimated at 2.87 Mg CO_2-C ha^{-1} per year (instead of 4.37 Mg CO_2-C ha^{-1} per year). Using this estimate, the CO_2 emission from residue decomposition was adjusted at 4.86 Mg C ha^{-1} per year and the amount of unaccounted residue-C was estimated at 0.25 Mg C ha^{-1} per year. This amount could be associated with faunal activity as discussed above, as well as other pathways of C loss including emission of methane, non-methane volatile organic compounds and DOC leaching.

It is important to caution that the rates of C increment reported in Table 3 are higher than commonly found in US cropland (see reviews by Lal et al., 1998; Follett, 2001). However, with manure and N fertilization, SOC accumulation rate averaging 1.5 Mg C ha^{-1} per year has been reported for a corn–wheat–clover rotation in Missouri (Buyanovsky and Wagner, 1998). Similarly high rates of C sequestration have also been reported during restoration of degraded lands (Bayer et al., 2000; Akala and Lal, 2001). A contributing factor to the high rates of C gain recorded in this study is probably the amount of residue applied which was 2.7–5 times greater than the average (2.9 Mg ha^{-1} per year) amount of residue generally left by a wheat crop (Allmaras et al., 1998).

5. Conclusions

This paper presents data on annual and seasonal CO_2 emission from soils in relation to N fertilization and wheat residue amendment. The results showed that N fertilization of residue had no significant effect on CO_2 flux, and therefore did not support the hypothesis that N addition stimulates biological activity and enhances CO_2 production. However, residue application had a significant effect on annual CO_2 loss and a marked influence on seasonal fluxes. Emission of CO_2 from the bare plots responded faster to temperature change while, in the mulch treatments, CO_2 fluxes showed delays before reaching their late winter peaks and their lowest levels in autumn. Annual CO_2 loss was proportional to the amount of residue added and amounted to 4.4, 6.5 and 7.7 Mg CO_2-C ha^{-1} in the bare, low mulch and high mulch treatments, respectively. Across treatments, between 17 and 22% of the total annual CO_2 emitted occurred in late winter underscoring the need to monitor CO_2 fluxes during soil thawing events to improve soil C budgeting. The average CO_2 flux in the bare soil was generally lower

than in the residue-amended plots in all seasons except during the summer when the average fluxes in all treatments were statistically similar. Consequently, summer CO_2 emission accounted for a larger share of the annual loss in the bare (43%) than in the other treatments (26%). These results demonstrated the influence of wheat residue cover on seasonal pattern of CO_2 emission from soils, presumably through alteration of soil thermal properties.

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